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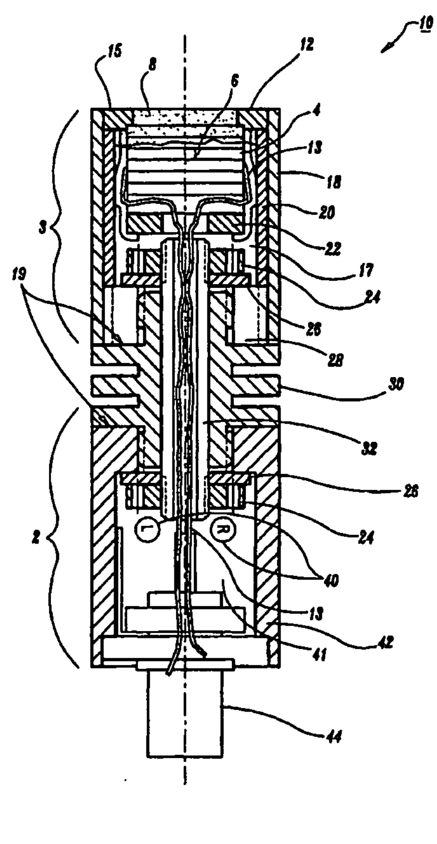

(57) Abstract: The present invention is a transducer (10) for sonically measuring gas flow. The transducer (10) includes a transducer body (18) defining a tube with a first end portion (3) of the tube including a damper portion for interfacing with the gas flow under measurement. The transducer also includes a membrane (12) rigidly attached to the transducer body for sealing off the transducer body from the gas flow. An actuator (6) made up of a stack of piezoelectric slices (4) is disposed in the transducer body (18) to interact with the membrane (12). An acoustic impedance matching material (8) having an acoustic impedance between the acoustic impedance of the actuator (6) and the acoustic impedance of the gas flow is disposed between the membrane (12) and the actuator (6). The transducer (10) further includes a damper assembly (20) disposed in the damper portion of the transducer body and consisting of a plurality of damping washers (30) disposed between acoustically transmitting washers (26) for damping acoustic energy through the transducer. Another embodiment of the transducer includes a reflector coupled to the first end portion for altering a direction of the acoustic energy directed to or form the transducer (10).

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TRANSDUCER FOR SONIC MEASUREMENT OF GAS FLOW AND RELATED CHARACTERISTICS

CROSS REFERENCE TO RELATED APPLICATION

This application claims priority to Provisional Application Serial No. 60/135,644 filed May 24, 1999.

BACKGROUND:

1. Field of the Invention

This disclosure relates to flow measurements and, more particularly, to sonic flow measurement devices for measuring gas flow characteristics.

2. Description of the Related Art:

Gas flow characteristics are difficult to measure using ultrasonic flow meters. This is in part due to the low density and ultimately to the impedance mismatch of sonic waves traveling from a transducer into the gas using conventional devices. Ultrasonic transducers typically employ a solid element for injecting ultrasonic energy into a fluid stream. In many instances, going from the solid to a fluid presents a sonic impedance mismatch and causes a large percentage of sonic energy to be reflected. For liquids, this mismatch is sufficiently small to permit ultrasonic measurements of the flow even when passing sonic energy through the metal wall of a pipe. For gas flow measurements, the impedance mismatch is high and is not easily overcome.

In addition, gas flow parameters are characteristically difficult to measure with sonic energy due to the low sonic impedance of the gas. Housings and pipe walls can also resonate or ring when sonic energy is input into the gas stream from an energetic transducer physically attached to the pipe wall. This resonance makes it difficult to identify and measure the sonic signal introduced into the gas stream.

Therefore, a need exists for an apparatus for accurately measuring flow in gas flows. A further need exists for an apparatus which is capable of being sufficiently coupled to the gas flow to overcome impedance mismatches and inject sufficient energy into the gas from a low voltage transmit source. A still further need exists for an apparatus which sonically isolates the apparatus from the pipe wall to avoid contamination of the gas sonic signal.

Summary of the Invention

A transducer for sonic measurements of gas flow, in accordance with the present invention, includes a housing having a first end portion, a membrane rigidly attached to the housing for sealing off the first end portion from a gas flow, and an actuator disposed in the first end portion for interacting with the membrane. An acoustically conductive material is disposed between the membrane and the actuator. The acoustically conductive material includes an acoustic impedance between an acoustic impedance of the actuator and an acoustic impedance of the gas flow.

In other embodiments, the transducer preferably includes a second end portion of the housing, and a damper

disposed between the first portion of the housing and the second portion of the housing for damping acoustic energy through the actuator. The damper may include a damping material having a discontinuous outer surface. The discontinuous outer surface may include fins and grooves. The damper may include a plurality of washers including alternating damping and transmitting washers. The actuator may include a stack of piezoelectric slices. The transducer may include a reflector coupled to the first end portion of the housing for altering a direction of acoustic energy directed to or from the transducer. The acoustic impedance of the conductive material may include a geometric mean of the acoustic impedance between the acoustic impedance of the actuator and the acoustic impedance of the gas flow. The membrane may include a metal which is displaced by the actuator to produce acoustic waves or is displaced by the gas flow to transmit acoustic energy to the actuator. The acoustically conductive material may include a thickness of a quarter wavelength of a wavelength generated by the actuator.

A transducer for sonic measurements of gas flow, includes a transducer body defining a tube having a first end portion, and a damper portion disposed adjacent to the first end portion, the first end portion for interfacing with a gas flow. A membrane is rigidly attached to the housing for sealing off the first end portion from the gas flow, and an actuator is disposed in the first end portion for interacting with the membrane. An acoustically conductive material is disposed between the membrane and the actuator. The acoustically conductive material includes an acoustic impedance between an acoustic impedance of the

actuator and an acoustic impedance of the gas flow. A damper assembly is disposed in the damper portion of the transducer body. The damper assembly includes a plurality of damping washers disposed between acoustically transmitting washers. The damper assembly damps acoustic energy through the transducer.

In alternate embodiments, the damper portion may include a wall thickness that is less than a wall thickness at the first end portion. The transducer body may include steel and the wall thickness of the damper portion is preferably between about 15 to about 25 mils. The actuator may include a stack of piezoelectric slices. The transducer may include a reflector coupled to the first end portion of the housing for altering a direction of acoustic energy directed to or from the transducer. The acoustic impedance of the conductive material may include a geometric mean of the acoustic impedance between the acoustic impedance of the actuator and the acoustic impedance of the gas flow. The membrane may include a metal which is displaced by the actuator to produce acoustic waves or is displaced by the gas flow to transmit acoustic energy to the actuator. The acoustically conductive material may include a thickness of a quarter wavelength of a wavelength generated by the actuator. The damping washers may include a thickness of a quarter wavelength of a wavelength generated by the actuator.

These and other objects, features and advantages of the present invention will become apparent from the following detailed description of illustrative embodiments thereof, which is to be read in connection with the accompanying drawings.

Brief Description of Drawings

The invention will be described in detail in the following description of preferred embodiments with reference to the following figures wherein:

FIG. 1 is a cross-sectional view of an apparatus for acoustically measuring flow in gases in accordance with the present invention;

FIG. 2 is a cross-sectional view of another embodiment of the apparatus for acoustically measuring flow in gases in accordance with the present invention;

FIG. 3 is a front view of a sonic reflector attached to the apparatus of FIG. 1 in accordance with the present invention;

FIG. 4 is a side view of the reflector attached to the apparatus of FIG. 1 in accordance with the present invention;

FIG. 5 is a rear view of the reflector attached to the apparatus of FIG. 1 in accordance with the present invention;

FIG. 6 is a cross-sectional view of the apparatus of FIG. 1 mounted in a pipe in accordance with the present invention;

FIG. 7 is a cross-sectional view of two apparatuses of FIG. 1 chordally mounted in a pipe with reflectors in accordance with the present invention; and

FIG. 8 is a cross-sectional view of an alternate embodiment of the apparatus for acoustically measuring flow in gases in accordance with the present invention.

Detailed Description of Preferred Embodiments

The present invention relates to flow measurements and, more particularly, to sonic flow measurement devices for measuring flow characteristics in a gas flow. The present invention provides an acoustically matched interface between the gas flow to be measured and the measuring apparatus. This interface preferably includes an acoustically conductive gel. The acoustically conductive gel is preferably a substantially incompressible material which transitions sonic energy between the apparatus and the gas flow to reduce impedance mismatch and thereby increase sonic energy transmission. The apparatus in accordance with the present invention also provides a damper internal to the apparatus for reducing sonic energy coupling from an active ultrasound producing device to the structure in contact with the pipe wall. The damper prevents sonic energy from being transferred to a housing of the apparatus. Further, an isolation portion of the apparatus is provided which permits attachment of the apparatus to a pipe or housing without transmitting or picking up resonance or other vibrational effects to or from the housing or pipe wall.

Referring now in specific detail to the drawings in which like reference numerals identify similar or identical elements throughout the several views, and initially to FIG. 1, an apparatus 10 in accordance with the present invention is shown. Apparatus 10 includes a stack or active element 6 which provides acoustic waves, preferably ultrasound waves for sonically measuring gas flow characteristics in a pipe or other medium. Apparatus 10 may be used as both a transmitter and a receiver for sonic energy. Apparatus 10 includes a housing 18 which is preferably a metal, such as

steel, stainless steel, titanium, etc. Housing 18 is configured and dimensioned to provide protection for the internal components of apparatus 10.

Active element 6 (herein after, stack 6) preferably includes a piezoelectric stack or a magneto-restrictive stack. In a preferred embodiment, stack 6 includes a plurality of thinly sliced lead metaniobate piezoelectric crystal layers 4, each layer 4 is poled opposite the adjacent layers to synchronously expand and contract the stack. Electrical connection to contacts between layers is made about the periphery of stack 6 such that a potential difference is created across each wafer or layer 4 when voltage is applied. Electrical connections 13 are epoxied in place before stack 6 is bonded within housing 18. Stack 6 expands and contracts in unison to achieve an amplitude of excursion. This amplitude of excursion is applied via a 1/4 wavelength impedance matched interface to a thin metal membrane 12 which is rigidly attached to housing 18, by, for example, electron beam welding. Membrane 12, in turn, causes compression waves to propagate in a gas flow, or if in receive mode, membrane 12 transmits sonic energy to stack 6 which converts the sonic energy to an electrical signal.

In accordance with the present invention, an acoustically conductive material 8 is disposed between membrane 12 and stack 6. Material 8 is preferably a substantially incompressible material which provides an acoustic impedance as close as possible to the geometric mean $(\sqrt{Z1 \cdot Z2})$ between the acoustic impedance of stack (Z1) and a gas flow (Z2) to be measured. Materials such a ULTEM™, TORLON™ or TEFLON™ may be employed. Acoustic

impedance is known by those skilled in the art, to be proportional to the density of a material and the acoustic velocity of the material. In this way, an acoustic gel may be selected based on the application and the physical properties of the apparatus and the gas to be measured. Since membrane 12 is thin, it is "acoustically invisible" and its effect is negligible on the impedance calculation. Material 8 is also selected based on its temperature and pressure capabilities. Some applications of the present invention may include temperatures greater than 550 F and pressures greater than about 6000 psi. Other temperatures and pressures may be used as well. Material 8 is preferably 1/4 the wavelength of the frequency of transmission of the acoustic wave. Material 8 may be approximately 0.1 inches in thickness. Material 8 may also be made from TEFLON™ and may include a thickness of about 0.12 inches. Housing 18 may be made from steel or titanium, for example, with a damper 20 made from TEFLON™ and integrally formed therewith.

Stack 6 is deployed in housing 18. A spacer 15 may be employed to assure proper spacing of stack 6 within housing 18 and to support material 18 from membrane 12. Spacer 15 is may be about 1/4 wavelength in thickness of the wavelength of the acoustic waves generated by stack 6. Spacer 15 may be made from a plastic, such as TEFLON, and the membrane 12 may include a metal, such as steel or titanium with a thickness of between about 5 to 10 mils. Spacer 15 may also be included to support and position stack 6 and material 8 and to provide space along the sides of stack 6 for electrical connections 13 and epoxy to flow during bonding as will be explained.

In accordance with the present invention, a damper 20 is provided between stack 6 and housing 18. Damper 20 is fit into housing 18 by a shrink fit or by applying an adhesive or epoxy therebetween. Damper 20 sonically damps any energy that enters housing 18 from either membrane 12 or internal paths. This energy is advantageously damped such that the retained energy does not interfere with low amplitude signals that result due to high attenuation of sonic signals as they pass through the gas flow.

Stack 6 is supported by a pressure backing plate 22 to provide support for stack 6 and provide a compression disk to permit passage of electrical connections 13 to stack 6. Prior to filling a cavity 17 with epoxy or silicone, a metal closure 28, for example, steel, is fitted with a nut 24 and a sonic isolation washer 26. Nut 24 will accept a center tube 32 which will be described below. Closure 28 is threaded into housing 18 and the threads sealed with epoxy. Closure 28 includes internal threads for attaching a sonic isolator 30 therein. Nut 24, washer 26 and closure 28 may include anti-rotation mechanisms, such as pins, flats, etc. Cavity 17 is now filled with epoxy to provide backing for stack 6 against high pressure gas flows.

In accordance with the present invention, sonic isolator 30 isolates sonic energy from a mounting portion 2 of apparatus 10 and a transducer portion 3 of apparatus 10. Center tube 32 is threaded into closure 28 and includes a hole therethrough to permit electrical connections to stack 6 to pass therethrough. Advantageously, center tube 32, which is preferably a metal, connects mounting portion 2 to transducer portion 3 and is sonically isolated by being surrounded by damping materials (e.g., TEFLON) to prevent

sonic energy from being introduced into center tube 32 and from being transmitted by center tube 32. This is performed by employing washers 26 and isolator 30 which are preferably formed from damping materials such as TEFLON. Isolator 30 preferably includes a discontinuous surface including fins or grooves to further prevent sonic energy passage. Washers 26 and isolator 30 prevent the passage of sonic energy from transducer portion 3 to mounting portion 2. Such sonic energy, if present, would interfere with measuring signals which are received from the gas flow during operation.

In addition to being held together by center tube 32 and nuts 24, transducer portion 3 and mounting portion 2 may be adhesively joined and sealed at surfaces 19 by using an epoxy of other bonding agent. This pressure seals these interfaces to prevent gas ingress.

Mounting portion 2 includes a pipe mount 42 which is a housing used to protect portions of a connector 44, electronic tuning components 40 and electrical connections 13. A cavity 41 may optionally be filled with an epoxy or other material. Also, center tube 32 is preferably filled with an epoxy or other material to prevent gas ingress and to fill any voids. Center tube 32 may include flared ends for coupling to housing 18 and pipe mount 42 through a sonically isolated material. Other attachment devices may also be employed.

Pipe mount 42 is preferably a metal such as steel, stainless steel, titanium, etc. Pipe mount 42 may include various mounting adaptations for mounting apparatus into a gas flow stream through a pipe wall for example. Such adaptations may include a connector plate, an extender tube, a compression mount or seal, flange mount or hot tap valve

fitting or other mechanism for adapting the mounting portion 2 for a particular application into a pipe wall or other mounting wall or surface. Advantageously, compression mounts or seals are able to be practiced due to isolator 30 of the present invention.

Stack 6 may be energized by applying a voltage across layers 4. In a preferred embodiment, a multi-pulse transmission may be employed in which a plurality of pulses are introduced and received. The techniques employed in U.S. Patent No. 5,117,698 may be employed. For example, initially, a short pulse train is transmitted and the total transit time between transmit and receive (t_N) is measured. The transit time in fluid is taken to be t_N, less the known length of time the acoustic signals remain in the transducers and the pipe walls t_F. Then, to measure flow rate, this method transmits a pulse train of substantial length (N) and detects a received pulse train (Rx) whose central portion (following initial transient effects) has the same frequency as the transmitted pulse train. Then, it is only necessary to detect the portion of the received signal which is phase coherent with the transmit signal, and measure the phase difference between the transmitted and received signals, to determine the upstream-downstream time difference (delta t), and thereby the flow rate.

Thus, the time difference delta t is calculated as a function of such phase difference, according to a formula.

The length N of the pulse train is selected to be the maximum delta t that is permitted without causing overflow of a delta t register of the particular embodiment. In this method, an initial setup routine tests a range of ultrasonic frequencies and determines an optimum frequency before flow

rate measurements are made.

The received pulses are stored and analyzed to determine gas flow characteristics, for example, the velocity of flow, the flow rate, the gas sonic velocity, the gas density and additional measurement parameters, such as pressure and temperature, etc. The value of the pulses may be sampled over time and averaged to converge at a characteristic value of the flow. This provides a stable and accurate result since a determination of transmitted and received pulses can be made based on the characteristics of the stored pulses. Signal processing techniques may be employed to decipher the correct signals to be used to measure flow characteristics of the gas flow. The correct signals, and not the vibrations and noise which may be present, are than used to determine the gas flow characteristics.

Further, since isolation is provided as well as distinct multi-pulse signals, the present invention can achieve signal to noise ratios of greater than 1000 to 1. This is achievable with voltages to stack 6 of only about 15 volts peak, for example, however other voltages may be used, for example, up to about 300 volts. Low voltage operation is preferred for safety concerns.

The present invention may be employed in any gas flow. In preferred embodiments, apparatus 10 is employed in pipes or furnaces for measuring characteristics of gas flows in, for example, flare gases, natural gases and steam.

Referring to FIG. 2, an alternate embodiment of the present invention is shown. An apparatus 100 includes all the components of apparatus 10 except stack 6 is directed substantially orthogonally to a longitudinal axis of

apparatus 100. A back plate 102 is employed to secure stack 6 after installation. Back plate 102 is then welded onto a housing 104 to provide support for stack 6.

Referring to FIGS. 3, 4 and 5, a reflector 200 may be employed on apparatus 10 (or apparatuses 100 and 150) to redirect transmitted acoustic waves or directionally receive acoustic waves. Reflector 200 provides for chordal or angulated sonic beam injection with a normally (normal mounting direction relative to a pipe wall) mounted transducer. Reflector 200 includes a plate 202 for reflecting the acoustic energy. Plate 202 is preferably a rigid material such as a metal, for efficiently directing a sonic wave. A window 204 is provided to permit directional propagation of the sonic wave. Reflector 200 may be detachable or permanently affixed to transducing portion 3 of apparatus 10. Reflector 200 may be configured to permit an angle adjustment or may be available with different angles for plate 202 relative to the direction of the stack 6. Holes 206 are also included to minimize hindrance to gas flow during operation.

Referring to FIG. 6 and 7, two mounting schemes are shown for the present invention. Although angular mounting may be employed for apparatus 10, normal mounting as shown is preferred. For a chordal mounting, apparatus 10 may be fitted with reflector 200 in a pipe 300 having a gas flow therethrough. Reflector 200 directs a transmitted signal to a second apparatus 10 which may include a reflector 200 to assist in receiving the signal. Chordal mounting is preferred for pipes which are access limited. Since the Reynolds number is fairly constant across a gas flow, ultrasound flow measurements may be made anywhere across the

flow. Other mounting schemes are contemplated as known in the art. For example, hot tap mountings may be employed where the transducer is mounted in a separate pipe and the transducer is flush or recessed from the inside diameter of the pipe with the gas flow to be measured.

Referring to FIG. 8, another embodiment of the present invention is illustratively shown. A transducer assembly 150 includes a transducer body 103, which preferably includes a metal tube, for example, stainless steel, steel or titanium. A front portion 104 is configured and dimensioned to receive stack 6 therein, and is similar to the front end portion as described for the embodiment of FIG. 1. Stack 6 is set in a filler material 108, for example, an epoxy, which preferably is free from voids. Front portion 104 includes a shoulder 106 which provides a surface to counteract pressure applied by a fluid on stack 6 when filler material 108 is cured. Transducer body 103 includes a damper portion 110. A thickness of damper portion 110 of transducer body 103 is reduced to preferably between about 5 mils to about 30 mils, and more preferably between about 15 mils to 25 mils. This reduction in thickness (from the thickness of end portion 104) provides less acoustic energy transfer from front portion 104 (which is in contact with or at least partially inserted in the fluid to be measured) to a back portion 112. In addition, thin walls of damper portion 110 provide transfer of acoustic energy to washers 114 of damper assembly 115.

Damper assembly 115 includes a plurality of acoustic energy transmitting washers 114 and a plurality of damping washers 116. Washers 114 preferably include a metal, such as stainless steel, steel or titanium, while damping washers

116 preferably include a damping material, such as a plastic, such as PTFE (e.g., TEFLON). Washers 114 and 116 alternate in damper assembly 115 (labeled as S and T). Washers 114 and 116 are bonded to transducer body 103 by employing a bonding agent or adhesive. Washers 114 and 116 permit stack wiring (not shown) to pass through their center regions. Advantageously, washers 114 draw acoustic energy from transducer body 103 in damper portion 110. The energy transmitted to washers 114 is damped out by washers 116. Damper assembly 115 therefore damps most if not all of the acoustical energy from stack or from a pipe or other mounting which is in contact with transducer 150. In a preferred embodiment, washers 116 include a thickness of 1/4 wavelength of the measured acoustic wavelength (e.g., the wavelength transducer 150 is designed to measure or designed to transmit). In this way, destructive interference reduces transmitted acoustic energy between front portion 104 and back portion 112. Washers 114 and 116 also provide support of transducer body 103 in damper portion 110, which is relatively thin.

A filler material 120 fills the center portions of washers 114 and 116 and fills a portion of back portion 112. Filler material 120 may include a silicon rubber, for example. A circuit board 122, for example a printed wiring board, and a circuit component 124, for example an inductor circuit or component may be included. Board 122 and component 124 may be employed to condition, power, amplify or otherwise act upon the signals coming from stack 6 or to supply power to stack 6. Terminal pins 126 are provided to permit connects to stack 6, circuit board 122 and/or component 124. In a preferred embodiment, coaxial cable 128

is employed although other cables or cabling methods may be employed.

It is to be understood that the embodiments described herein may be used alone or may have their components combined to provide a different configuration adapted to a specific task or application. Further, portions of each embodiment may be modified to provide customized fits or to otherwise make the devices of the present invention compatible with different applications or set ups. For example, transducers may be configured and dimensioned to standard O-ring sizes, or threaded to permit engagement with pipes or other gas or fluid carrying media.

Having described preferred embodiments of a transducer for acoustically measuring gas flow characteristics (which are intended to be illustrative and not limiting), it is noted that modifications and variations can be made by persons skilled in the art in light of the above teachings. It is therefore to be understood that changes may be made in the particular embodiments of the invention disclosed which are within the scope and spirit of the invention as outlined by the appended claims. Having thus described the invention with the details and particularity required by the patent laws, what is claimed and desired protected by Letters Patent is set forth in the appended claims.

WHAT IS CLAIMED IS:

1. A transducer for sonic measurements of gas flow, comprising:

a housing having a first end portion;

a membrane rigidly attached to the housing for sealing off the first end portion from a gas flow;

an actuator disposed in the first end portion for interacting with the membrane;

an acoustically conductive material disposed between the membrane and the actuator, the acoustically conductive material including an acoustic impedance between an acoustic impedance of the actuator and an acoustic impedance of the gas flow.

2. The transducer as recited in claim 1, further comprising:

a second end portion of the housing; and

a damper disposed between the first portion of the housing and the second portion of the housing for damping acoustic energy through the actuator.

3. The transducer as recited in claim 2, wherein the damper includes a damping material having a discontinuous outer surface.

4. The transducer as recited in claim 3,wherein the discontinuous outer surface includes fins and grooves.

5. The transducer as recited in claim 1, wherein the actuator includes a stack of piezoelectric slices.

6. The transducer as recited in claim 1, further comprising:

a reflector coupled to the first end portion of the housing for altering a direction of acoustic energy directed to or from the transducer.

7. The transducer as recited in claim 1, wherein the acoustic impedance of the conductive material includes a geometric mean of the acoustic impedance between the acoustic impedance of the actuator and the acoustic impedance of the gas flow.

8. The transducer as recited in claim 1, wherein the membrane includes a metal which is displaced by the actuator to produce acoustic waves.

9. The transducer as recited in claim 1, wherein the membrane includes a metal, which is displaced by the gas flow to transmit acoustic energy to the actuator.

10. The transducer as recited in claim 1, wherein the acoustically conductive material includes a thickness of a quarter wavelength of a wavelength generated by the actuator.

11. A transducer for sonic measurements of gas flow, comprising:

a transducer body defining a tube having a first end portion, and a damper portion disposed adjacent to the first end portion, the first end portion for interfacing with a gas flow;

a membrane rigidly attached to the housing for sealing off the first end portion from the gas flow;

an actuator disposed in the first end portion for interacting with the membrane;

an acoustically conductive material disposed between the membrane and the actuator, the acoustically conductive material including an acoustic impedance between an acoustic impedance of the actuator and an acoustic impedance of the gas flow; and

a damper assembly disposed in the damper portion of the transducer body, the damper assembly including a plurality of damping washers disposed between acoustically transmitting washers, the damper assembly for damping acoustic energy through the transducer.

12. The transducer as recited in claim 11, wherein the damper portion includes a wall thickness that is less than a wall thickness at the first end portion.

13. The transducer as recited in claim 12, wherein the transducer body include steel and the wall thickness of the damper portion is between about 15 to about 25 mils.

14. The transducer as recited in claim 11, wherein the actuator includes a stack of piezoelectric slices.

15. The transducer as recited in claim 11, further comprising:

a reflector coupled to the first end portion of the housing for altering a direction of acoustic energy directed to or from the transducer.

16. The transducer as recited in claim 11, wherein the acoustic impedance of the conductive material includes a geometric mean of the acoustic impedance between the acoustic impedance of the actuator and the acoustic impedance of the gas flow.

17. The transducer as recited in claim 11, wherein the membrane includes a metal which is displaced by the actuator to produce acoustic waves.

18. The transducer as recited in claim 11, wherein the membrane includes a metal, which is displaced by the gas flow to transmit acoustic energy to the actuator.

19. The transducer as recited in claim 11, wherein the acoustically conductive material includes a thickness of a quarter wavelength of a wavelength generated by the actuator.

20. The transducer as recited in claim 11, wherein the damping washers include a thickness of a quarter wavelength of a wavelength generated by the actuator.

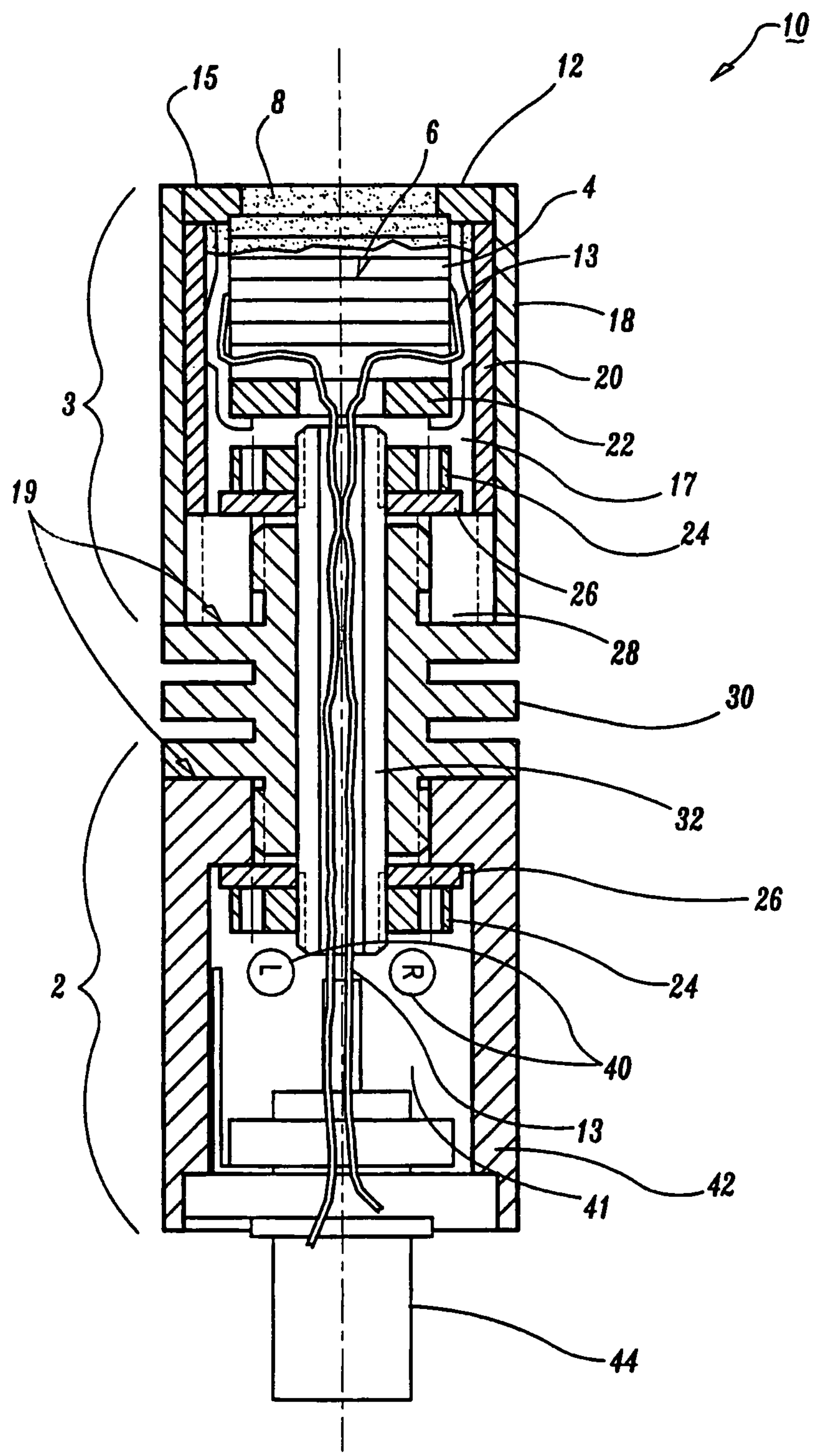

FIG. 1

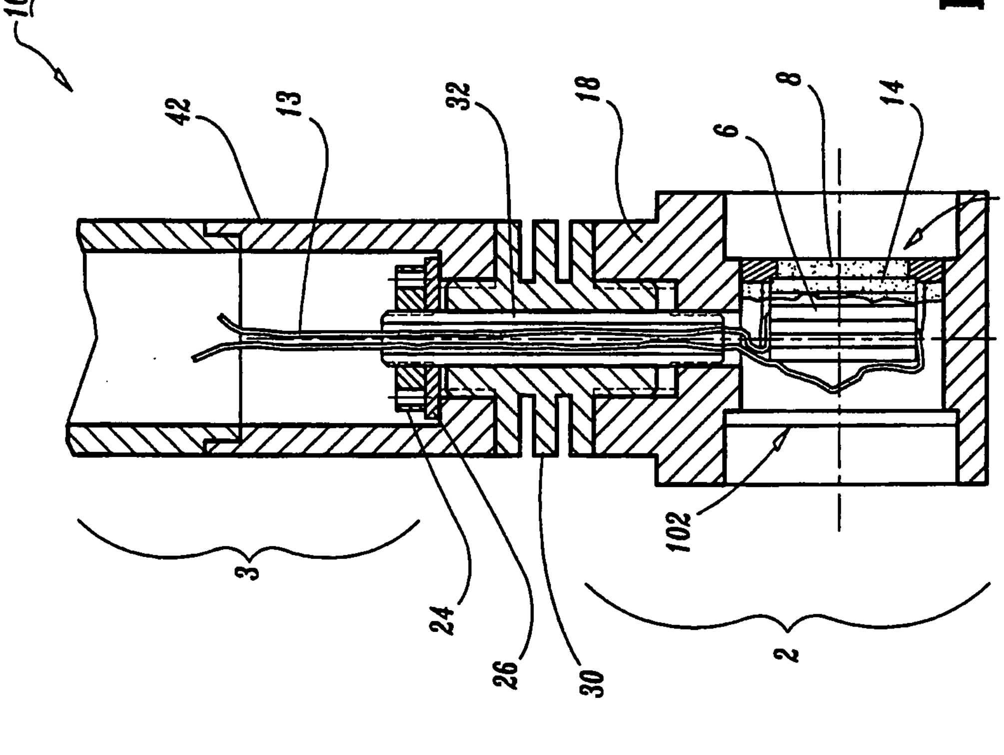

FIG. 2

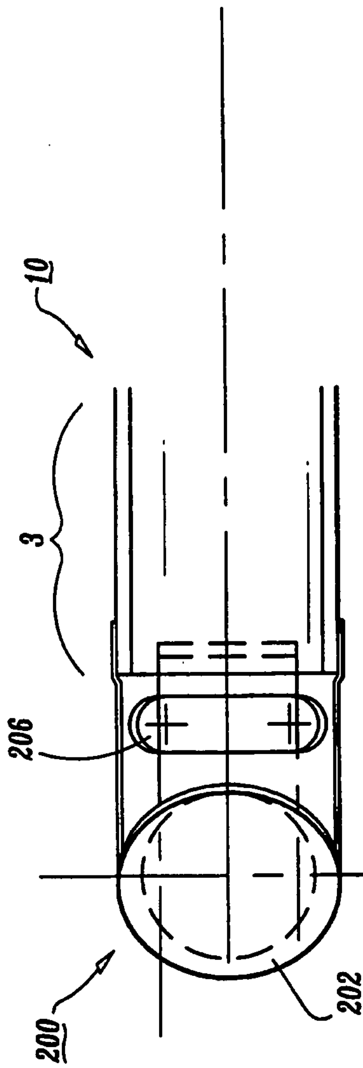

FIG. 5

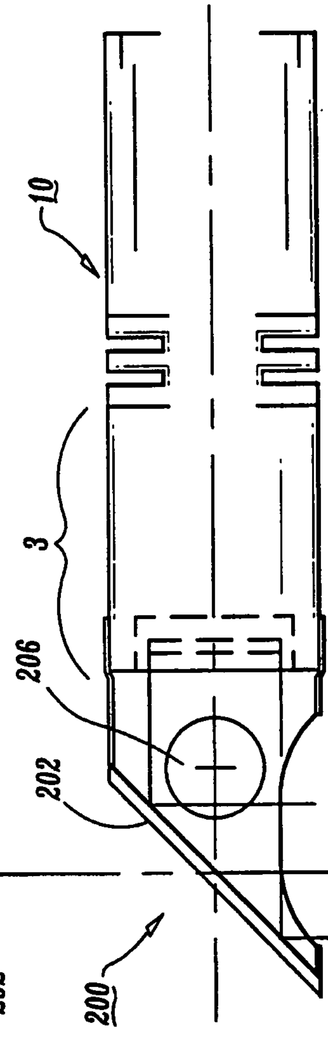

FIG. 4

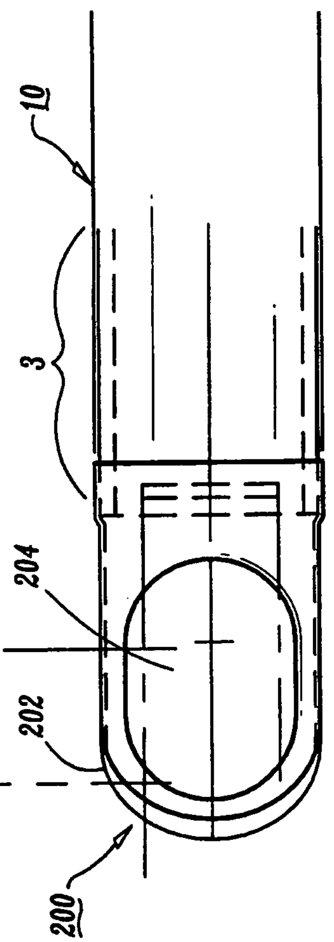

FIG. 3

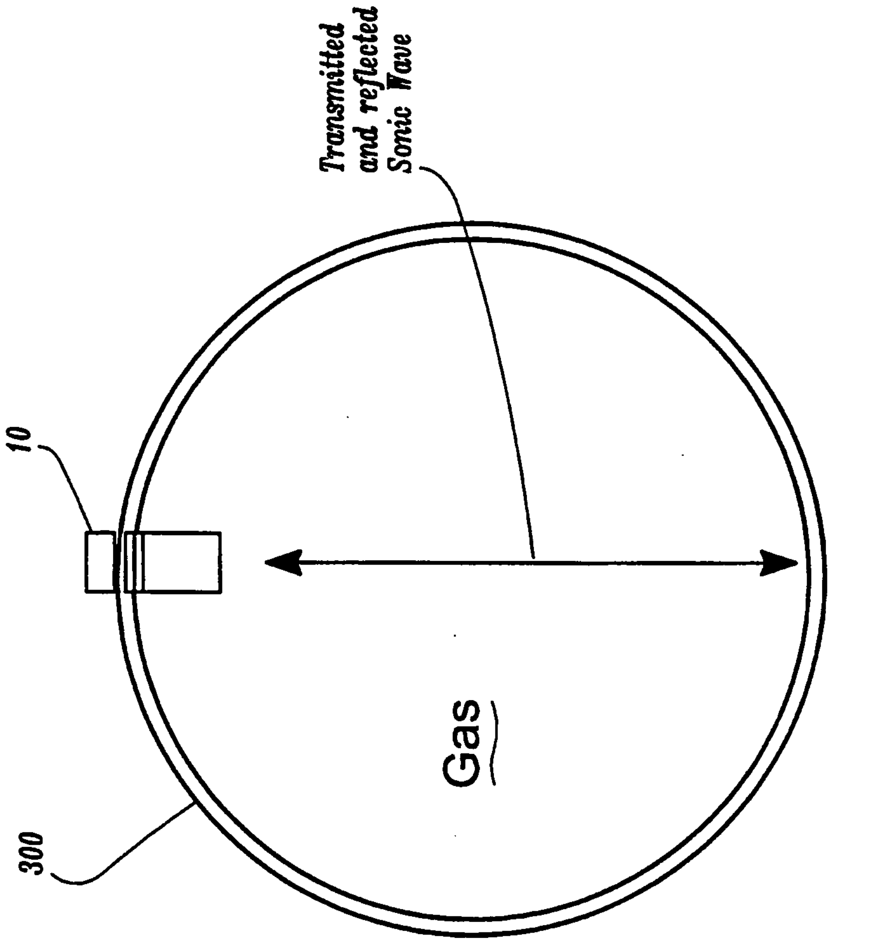

FIG. 6

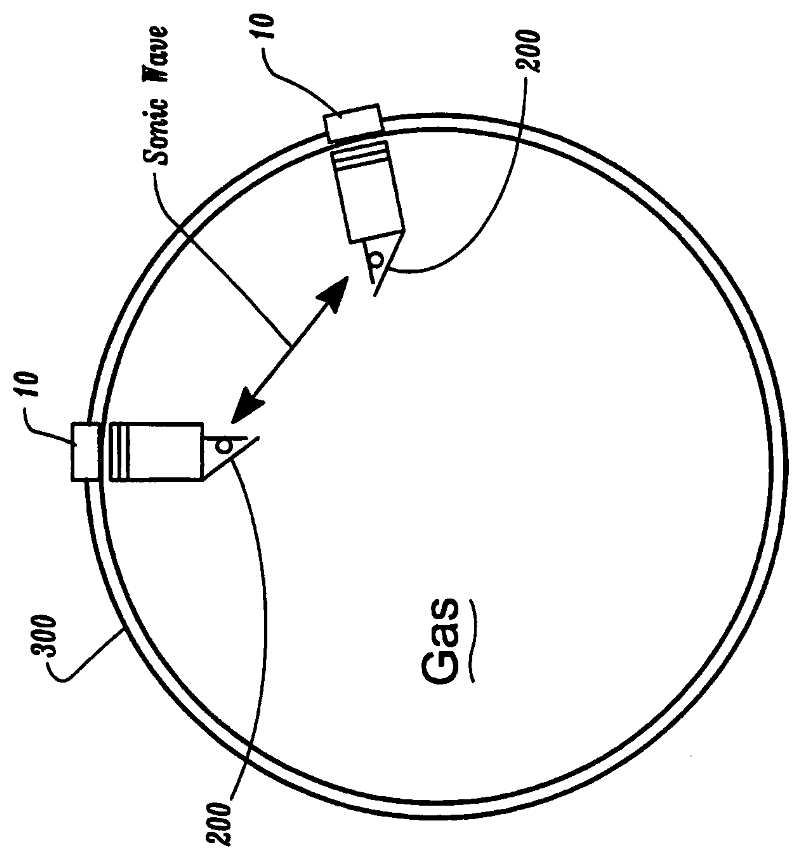

FIG. 7

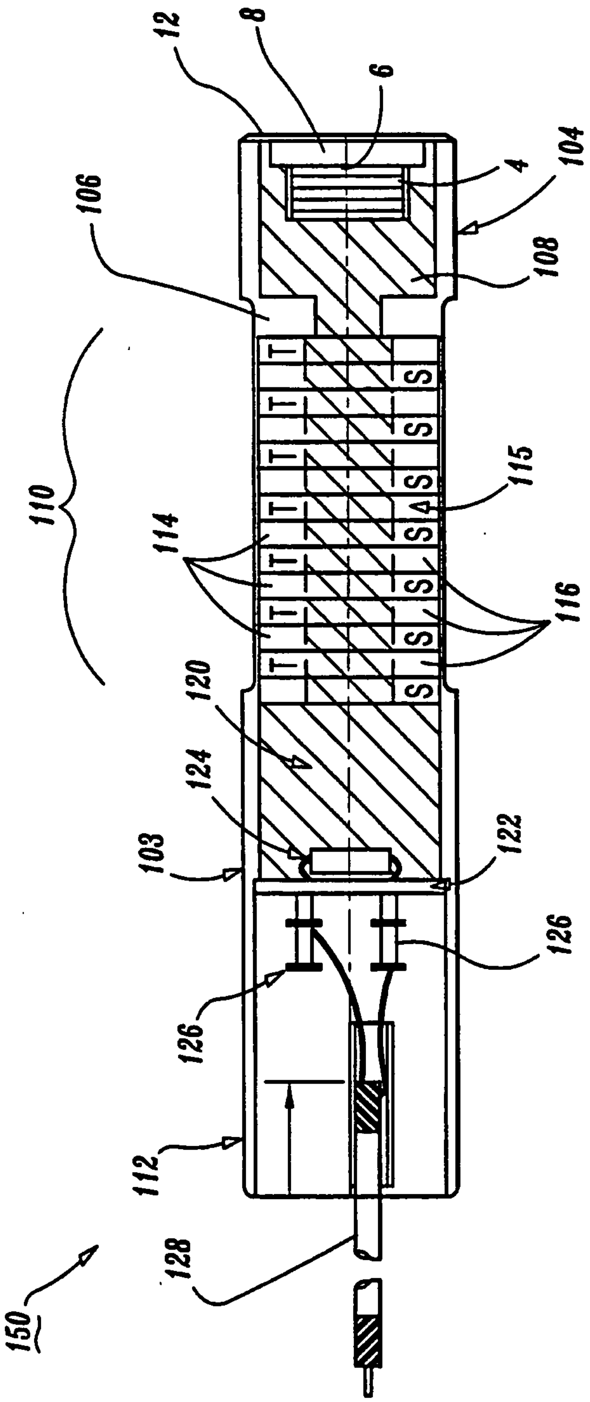
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FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/14213

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) : G01N 29/04
US CL : 73/632, 644
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 73/632, 644, 861.18, 861.25, 861.26, 861.27, 861.28, 861.29, 861.31

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EAST: acoustic, ultrasonic, ultrasound, foil, membrane, gaseous, gas, diaphram, impedance matching

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,646,754 A (ZACHARIAS) 17 March 1987 (17.03.1987) see abstract, Figures, and column 1 line 10 - column 3 line 31.	1-20
Y	US 5,159,838 A (LYNNWORTH) 03 November 1992 (03.11.1992) see abstract, Figures, column 4 line 35 - column 5 line 9, and column 6 line 57 -column 8 line 27.	6, 15
X --- Y	US 5,275,060A (LYNNWORTH) 04 January 1994 (04.01.1994) see abstract, Figures, column 1 lines 49-68, column 2 lines 31-68 and column 4 lines 11-39.	1-5, 7-10 --- 6
X --- Y	US 5,515,733 A (LYNNWORTH) 14 May 1996 (14.03.1996) see abstract, Figures, column 1 line 50 - column 2 line 46, column 3 line 38 - column 4 line 33 and column 5 line 40 - column 6 line 5.	1-5, 7-14, 16-20 --- 6 and 15

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 July 2000 (11.07.2000)	31 JUL 2000

Name and mailing address of the ISA/US	Authorized officer
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